【Grant-in-Aid for Scientific Research (S)】

Pioneering study of excited charmed baryons using high-momentum pion beams

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Purpose and Background of the Research

●Outline of the Research

“How is matter built from quarks?” is a fundamental question in the evolution of matter in the universe. Just after the Big Bang, when the universe was still at a high temperature, quarks were free from each other. As the universe cooled, quarks were bound to each other, forming hadrons. Hadrons are classified into mesons and baryons. A baryon comprises 3 quarks. Protons and neutrons (nucleons, hereafter) are stable baryons. A set of nucleons bound by the nuclear force have formed atomic nuclei. Atomic nuclei binding electrons have formed atoms, which have made various materials existing around us. We find that the baryons are the first complex systems made up of elementary particles. After all, we reach a question “how quarks build baryons” starting from the question asked at the beginning. The “strong force (strong interaction)” acts on quarks. The strong force is really strong and its behavior is complicated as the nature of vacuum changes. As a result, baryon masses are generated and quarks are confined in a baryon. Since a single quark cannot be extracted from a baryon, we could obtain information on the quark motion in a baryon through investigating nature of excited baryons such as their masses, production rates, and decay properties. Revealing the nature of the strong interaction to form baryons, we could understand the nature of matter in extreme conditions formed by the strong interaction, such as highly-dense baryonic matter in neutron star cores in which the density is far beyond that of nuclei or ultra-high-density quark matter where quarks are free from baryons.

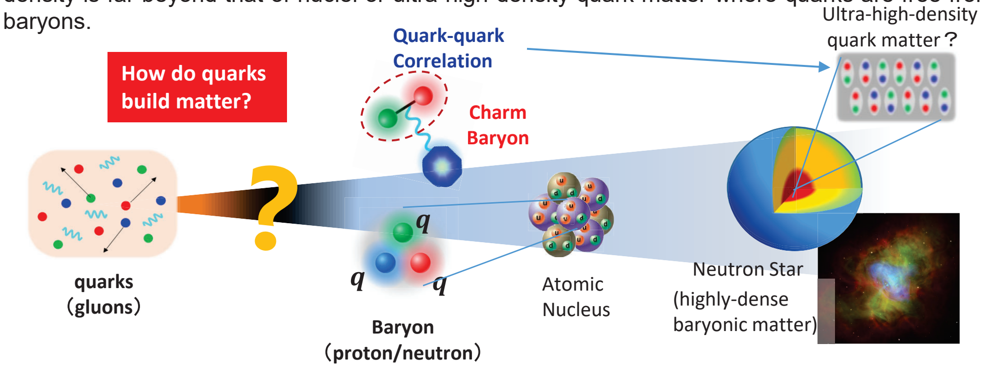

Figure 1. Matter evolution in the universe

●Motions of quarks in charm baryons

In ordinary baryons like nucleons comprising quarks with an approximately equal mass, it is difficult to separate quark motions since 3 quarks are entangled. We find that quark motions are disentangled by replacing a light quark by a heavy charm (c) quark which is approximately 5 times heavier than the light quark. As shown in Figure 2, an excitation energy of a collective motion of the light quark pair to the c quark (λ mode) is lower than that of a relative motion between the light quarks (ρ mode). This is the so-called isotope shift seen universally in multibody systems. (to be continued)

●Motions of quarks in charm baryons (cont.)

Each excition mode is further split by spin-dependent forces. In the λ-mode excitation of a strongly correlated pair of light quarks with orbital angular momentum (L) relative to the heavy quark, it separates into two states depending on the spin orientation of the heavy quark with respect to L (spin doublet). By identifying these states, we will establish the quark pair correlation inside baryons, and obtain information on the spin-dependent forces acting between quarks.

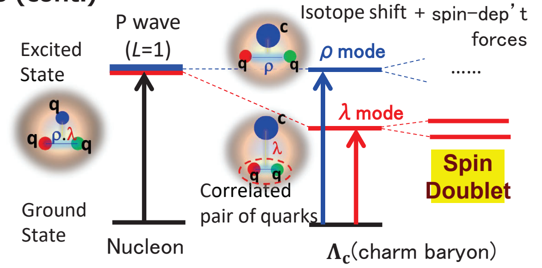

Figure 2. When a quark (q) in an ordinary baryon (nucleon) is replaced with a heavy charm quark (c), the motions of quarks inside a baryon are separated (isotope shift). The length of the arrow represents the mass difference between the states (excitation energy).

Expected Research Achievements

●internal structure of charmed baryons studied by their productions and decays

Figure 3 shows a production reaction of a charm baryon (Y_c^{*+}) associated with a D^{*-} meson by impacting a pion (π^-) on a proton (p). The Y_c^{*+} mass is measured by means of an energy difference between incoming pion’s and outgoing D^{*-}’s (missing mass). By doing so, we could measure a wide mass range of charm baryons as well as their production rates and decay branching ratios that reflect their internal structure. The reaction diagram indicates that a finite angular momentum (L) could be introduced between a charm (c) quark and correlated ud-quark pair, and thus a λ-mode state could be excited. Figure 4 shows expected mass distribution of charm baryons based on theoretical calculations of the production cross sections. We find that a ground state Λ_c charm baryon as well as spin-doublet λ-mode excited states with $L = 1, 2$ are populated clearly. The spin doublet states can be identified by the production ratio and decay pattern, providing information on the spin-dependent interaction between quarks. We will establish existence of a quark-pair correlation in baryons. The quark-pair correlation is expected to be a source of quark-pair condensation which characterizes ultra-high density quark matter. It is expected to provide important knowledge to understand matter in extreme conditions, such as neutron star cores.

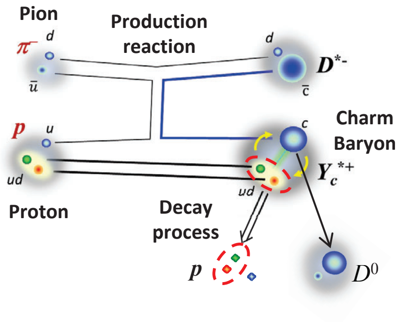

Figure 3. Production and decay of charm baryons

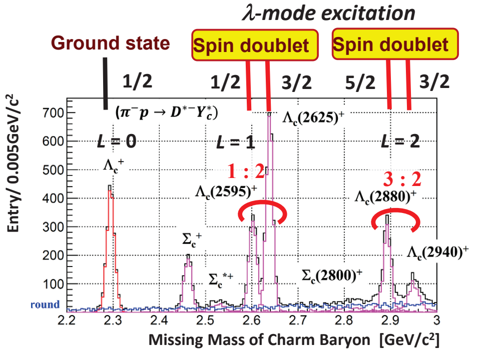

Figure 4. Expected mass distribution (spectrum) of charm baryons ($Y_c^{*+} = \Lambda_c^{*+}$ or Σ_c^{*+}).

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